Design and Thermo-Hydraulic Analysis of Upgraded PUMA System for the Development of a Test Facility of Superconducting CICCs

Dong Keun Oh, Keeman Kim, Hyun Joung Lee, and Qiuliang Wang

***Abstract*—As an activity to build a new test facility for superconducting CICCs (Cable In Conduit Conductors), an insertion coil for an upgrade of the existing CS (central solenoid) model coil of KSTAR was designed and analysed to implement a superconducting magnet system being capable of pulsed operation up to 12 T. On the basis of a developed winding scheme of the insertion coil, some candidates of CICC design were proposed according to the result of an optimization method and a numerical code examining the thermo-hydraulic stability of CICC. After the design of winding pack and CICCs, we investigated thermo- hydraulic behaviors of the superconducting magnet with respect to given scenarios to estimate the limit of safe operation in pulsed mode.**

***Index Terms*—CICC, KSTAR, superconducting magnet, thermohydraulic analysis.**

I. Introduction

THE central solenoid model coil (CSMC) of KSTAR was fabricated not only to estimate the performance of CS magnet of KSTAR but also to implement a background field magnet for a test facility for CICC short samples like SULTAN test or joint samples [1], [2]. The Helmholtz configuration of the pair of KSTAR CSMC reflects such a design concept which allows a conductor sample to access the high field region of that magnet easily with appropriate field homogeneity by putting the sample into the gap.

Originally, for the test facility, a "Blip-Coil" was designed and installed into the bore of main coil (KSTAR CSMC) to implement a very fast pulsed operation (20 T/s) of additional field up to ± 1 T by the exponential discharge of "Blip-Coil" with 50 ms time constant to exert expected states of EM disturbance of KSTAR operation on the test samples [2].

Recently, a necessity of upgrade for our superconducting test facility up to ± 12 T has been emerged according to recent efforts for verification of the feasibility of a practical magnetic fusion device [3]. While there is such a need of cost effective qualification tool for a short-sample conductor for reactor grade plasma devices, which are recently developing or will be implemented in the future, it is hard to say that such a propose can be fully answered by existing test facilities. For example, the ITER CS conductors are designed to operate in the pulsed magnetic field of relatively high magnitude, and the condition of such high and pulsed field cannot be achieved by any existing full-size short sample test device.

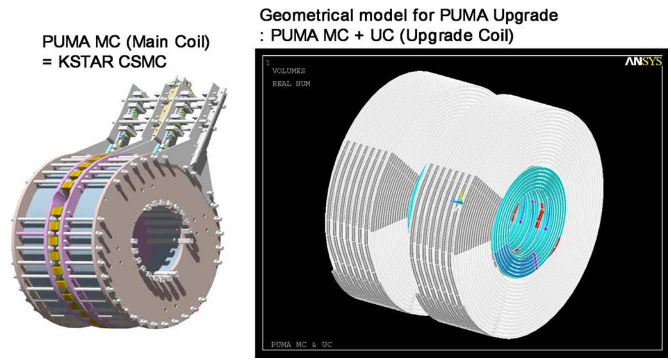

Fig. 1. 3D drawing of KSTAR CSMC(PUMA MC) (left) and a geometrical model for the coils of PUMA system(MC+UC) for the ANSYS environment (right). As shown in colors on the right figure, the upgrade coil is inserted into the main coil's bore.

Under the consideration of such a requirement, a design activity for the insertion coil was planed to upgrade the main coil of existing magnet system of the test facility for the development of KSTAR. The upgrade was designated to build a short-sample test device for the current-carrying performance of a conductor in the background field of up to 12 T with the pulsed operation capability. According to such an activity, a new design of upgraded magnet was proposed so called "PUMA (PUlsed MAgnet) system".

The PUMA system is presented in the Fig. 1 in which a geometric model of upgraded PUMA system, which is actually developed for the magnetic field calculation using FEM package, is shown to make it understood that the upgrade coil (UC) will be inserted into the bore of KSTAR CSMC assembly which is the main coil (MC) of PUMA system.

In this paper, the PUMA-UC (Upgrade Coil) is introduced describing the detail feature of the winding pack and efforts to find out an appropriate CICC design through an optimization process and thermo-hydraulic stability analyses. With to the resultant numerical models for the PUMA-UC, the robustness of upgrade coil, when it is installed in the PUMA-MC, against

Manuscript received August 18, 2008. First published June 23, 2009; current version published July 15, 2009. This work was supported by the Korean Ministry of Science and Technology of Republic of Korea under the contract of ITER Korea project.

D. K. Oh, K. Kim, and H. J. Lee are with the National Fusion Research Center, Daejeon, Korea (e-mail: spinhalf@nfri.re.kr; kkeeman@nfri.re.kr; yaeban@nfri.re.kr).

Q. Wang is with the Institute of Electrical Engineering, Chinese Academy of Science, Beijing, China (e-mail: qiuliang@mail.iee.ac.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2009.2018787

TABLE I
PARAMETERS OF WINDING PACK

Parameter	Value
Outer Diameter [mm]	734.44
Inner Diameter [mm]	420
Coil Height [mm]	397.9
Number of turns	90
Number of layers	16
Total length of CICC [m]	164.3
Number of cooling channel	2

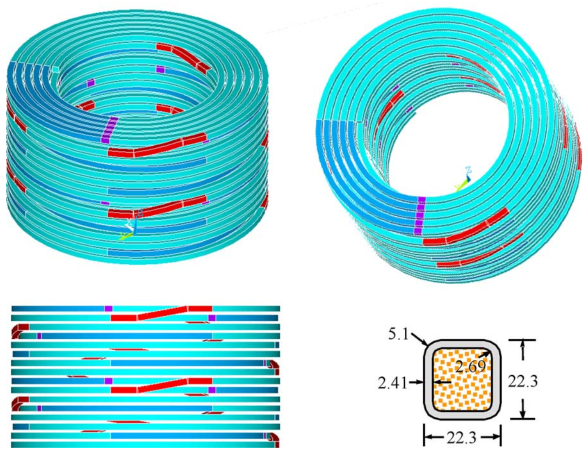

Fig. 2. Model for the winding scheme of PUMA-UC, and the dimensions of CICC(right and lower).

pulsed operation was examined under the condition of some extreme cases of operation scenario employing a numerical code of thermo-hydraulic analysis for superconducting CICCs.

II. Design for Upgrade

A. Winding Pack Design for PUMA-UC

To fit into the inner radius of the main coil ($\mathrm{inner\ radius} = 340\ \mathrm{mm}$, $\mathrm{outer\ radius} = 744\ \mathrm{mm}$), the dimensions and the winding scheme were carefully decided for the upgrade coil. Using the same CICC jacket as main coil (rounded square jacket: $\mathrm{w} = 22.3\ \mathrm{mm}$, $\mathrm{h} = 22.3$), we obtained the number of turns of 6 to achieve the inner radius as large as 210 mm for a sufficient field homogeneity on the magnet center (Table I).

A continuous winding scheme was established making an "exact circle" for the outline of round shape and the inner bore to fit the circle of inner radius of main coil. For every last turns (6th turn) of each layer, 1/4 turn should be omitted not to cross the guidelines of both exact circles, and additional 1/8 turn have to be missed for layer transition. As a result, 90 turns will be wound for a winding pack of 16 layers as shown in Fig. 2.

For the analysis, the magnetic field along the center line of CICC should be known, Thus, Biot-Savart calculation was done employing the SOURC36 element in ANSYS. Such a magnetic field distribution along the cooling path as in the Fig. 3 can be applied to the thermo-hydraulic analyses of CICC as an input data to the numerical code.

We assumed the maximum current of PUMA system is 22.3 kA, and, in such a condition, the magnetic field at the center

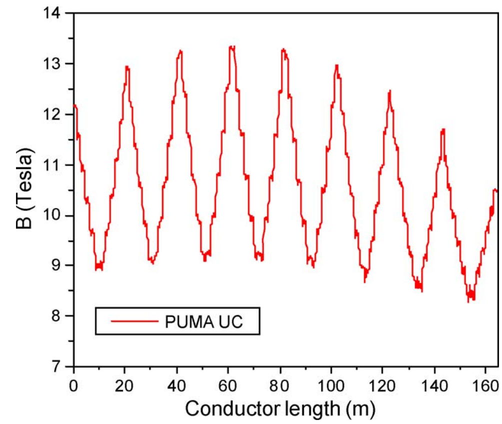

Fig. 3. Magnetic field distribution along the cooling path.: Operating current is 22.3 kA.

TABLE II
CICC PARAMETERS

Parameter	MC	UC (Design #1)	UC (Design #2)
Cabling Pattern		3x4x5x6	
(Pitches [mm])		(40x90x200x480)	
Superconductor		Nb3Sn	
Jacket Material		Incoloy 908	
1st triplet	1 Cu + 2 KSTAR	1 Cu + 2 KAT RC38	1 KSTAR + 2 KAT RC38
Strand Diameter [mm]	0.78±0.01	0.82±0.01	0.78±0.01 0.82±0.01
Cr Plating Thickness [mm]	0.001 ±0.0002	0.001 ±0.0002	0.001 ±0.0002
Jc(12T,4.2K) [A/mm^2]	780	890	780/890
Strand's Cu/nonCu	1.5	1.0	1.5/1.0
RRR	100	100	100
A_{jacket} [mm^2]	175.6	175.6	175.6
A_{tnonCu} [mm^2]	45.63	62.75	85.57
A_{Cu} [mm^2]	125.5	125.5	96.98
A_{He} [mm^2]	103.2	82.18	88.21
Void Fraction [%]	~36	~31	~33

of the PUMA system will be 12 T, and the highest field on the CICC will be 13.34 T.

B. CICC Design for PUMA-UC

The main coil's CICC consists of the same Nb_3Sn strands of KSTAR CS magnet [4]. At 13 T and 5 K, they show negative value of temperature margin which is not suitable to the CICC of PUMA-UC. Thus, several candidates of conductor design were investigated under the consideration of optimal design balancing the material fraction to maximize the operating current given by the constraint of temperature (or energy) margin within the limit of well-cooled regime [5].

There is a practical calculation tool for such an optimization for CICC design, which is well-known as OPTICON (CryoSoft). Some parts of the code were modified for the specific characteristic of the Nb_3Sn strand of KAT (Kiswire Advanced Technology) RC38 which was employed for the fabrication of SULTAN sample of the ITER TF conductor R&D in 2007 [6]. With a constraint of $\Delta T_{margin} > 3\ K$ and $f_{He} = 0.34$, we tried to find an optimal design which have an operating current above 20 kA. As a result, a CICC design

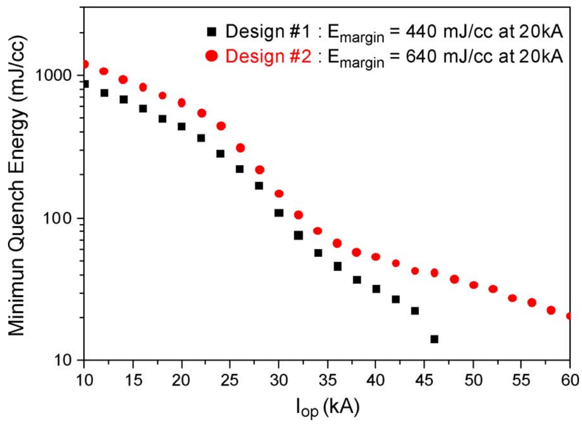

Fig. 4. Minimum quench energy vs. operating current at $B = 12$ T, $T = 5$ K: Stagnant flow (mass flow $= 0$ g/s) was assumed. An external heat pulse of Gaussian shape ($L = 6$ m) was deposited on the center of CICC during 10 ms.

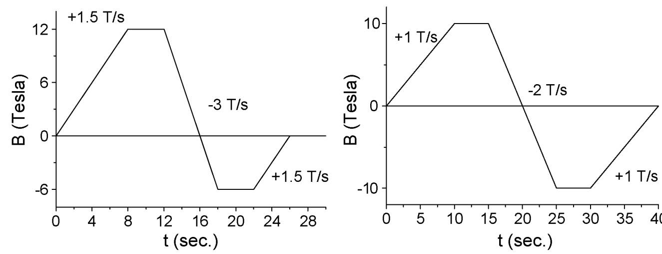

Fig. 5. Scenario #1 (left) and Scenario #2 (right) for thermo-hydraulic analysis.

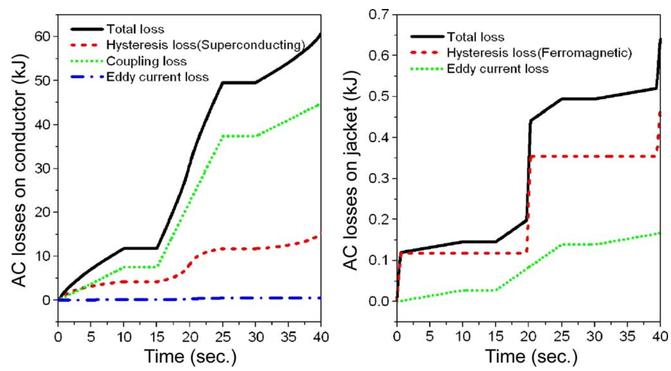

Fig. 6. Total deposited energies on the 1st cooling channel (82.05 m) according to the Scenario #2: Left figure is the energy on the conductor and right is on the jacket. The conductor under the calculation is Design #1. As shown in this figure, the major components of the heat load from AC losses are the coupling loss and the hysteresis loss on the conductor bundle. In our case, $n\tau$ of coupling loss is assumed as 20 ms.

was obtained as $f_{He} = 0.34$, $f_{Cu} = 0.44$ and $f_{nonCu} = 0.22$, and, with respect to the result, some essential characteristics of the proposed conductor are presented as $\Delta T_{margin} = 3.15$ K, $E_{margin} = 473$ mJ/cc, $T_{hot-spot} < 145$ K, $P_{max} < 40$ MPa.

On the basis of such a result, two candidates of CICC design were developed. The Design #1 is very close to the presented optimal design, but, in the Design #2, the conductor has relatively large total non-Cu area and small fraction of stabilizer due to the absence of pure Cu strand, which may be far from the optimal design, but is an alternative design taking into account the large heat load of pulsed mode.

The parameters of CICCs are presented in Table II.

For both designs, the energy margin of CICC can be estimated employing GANDALF (CryoSoft) code with some modification searching for the minimum amplitude of heat pulse which drives the CICC into quench. To calculate the minimum quench energy, DC heat pulse was applied during 10 ms, and such an external heat disturbance deposited on the center of CICC of 200 m with the Gaussian shape of spatial distribution with the characteristic length of 6 m [7]. For the simulation, the stagnant flow condition was assumed so that inlet and outlet pressure was maintained in 0.5 MPa. The energy margin for each design with respect to operation current is presented in Fig. 4.

For the Design #1 which is close to optimal design, estimated energy margin of 473 mJ/cc at 20 kA agrees well with OPTICON's estimation of 435 mJ/cc. As expected, larger energy margin of 640 mJ/cc at 20 kA was obtained for Design #2.

III. Operation Analysis in Pulsed Mode

A. Operation Scenario and Cooling Condition

After the calculations of the characteristic of designed CICCs, the thermo-hydraulic behaviors were investigated for the integrated PUMA system (MC+UC). For such an analysis, the hydraulic channels should be specified for the magnet system under the investigation. Especially, since the PUMA system is designed for the operations in pulsed mode, various AC losses should be taken into account as heat loads during the operation. We separated the total hydraulic path of CICC (164.3 m) of PUMA UC into two channels of flow path whose length is 82.05 m and 82.25 m for each. To satisfy such a cooling scheme, the helium inlet is located on the center of CICC where the magnetic field is highest to supply the supercritical fluid to the each channel, and, at the both ends of the coil, there are drains.

To investigate the safety in pulsed mode, two extreme cases of pulsed operation ($(dB/dt)_{max} = -3$ T/s and -2 T/s for each) were proposed as scenarios for the thermo-hydraulic analysis examining the temperature margin and other thermohydraulic characteristics with respect to the designs of CICC [8].

Assumed scenarios of magnetic field are shown in Fig. 5.

In every case, the inlet and outlet pressure are assume as 0.55 Pa and 0.4 MPa. The inlet and initial CICC temperatures are 5 K for the Scenario #1 and 4.5 K for the Scenario #2.

B. AC Losses as Heat Load

In the pulsed operation condition, conductors will experience various heat loads by AC losses such as the hysteresis loss of superconductor, the coupling and the eddy current loss [9]. Such losses can be treated as external heat sources which can be coded into the numerical routines as a part of thermo-hydraulic analysis program of CICCs in PUMA system.

Even though AC losses on the jacket is much smaller than the heat loads of the conductor itself, we considered the heat load on the conduit which is a sum of the ferromagnetic hysteresis loss and the eddy-current loss on the jacket material of Incoloy 908 [9] (Fig. 6).

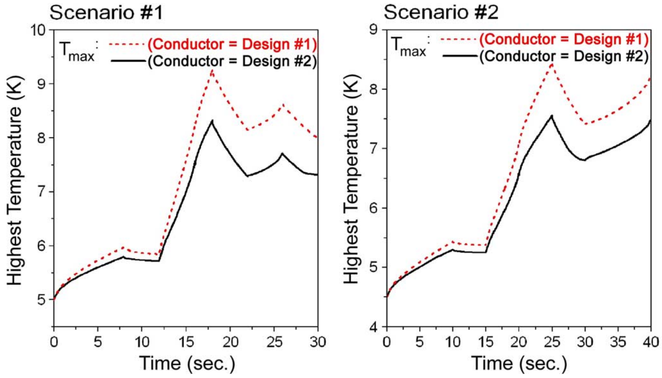

Fig. 7. Maximum temperatures of conductor during the operation with respect to Scenario #1 (left) and Scenario #2 (right).

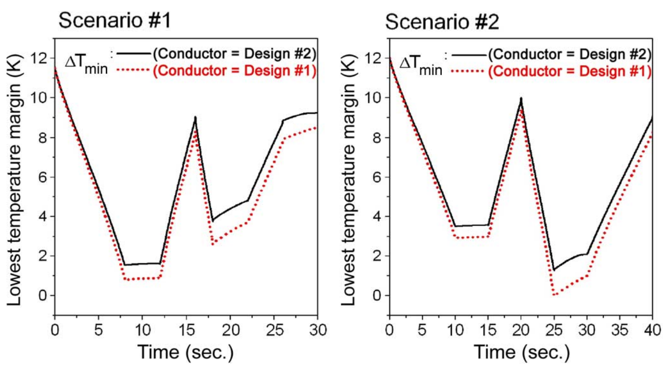

Fig. 8. Minimum temperature margin of conductors during the operation according to the Scenario #1(left) and the Scenario #2(right).

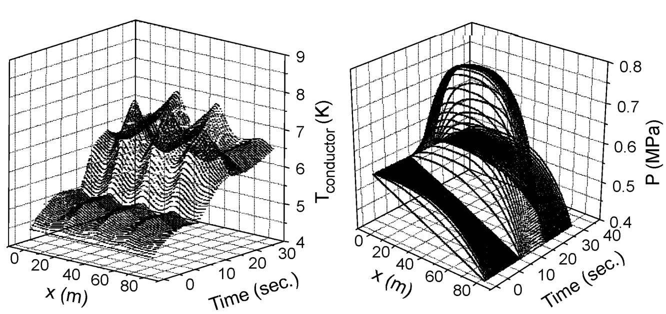

Fig. 9. Temporal evolution of the conductor temperature (left) and pressure (right).

C. Temperature Margin and Maximum Temperature

Applying the operation scenarios, the temperature margin and maximum temperature of conductor during the operation were computed for each conductor design [8]. Because of relatively extreme conditions for operation, the temperature margins were closed to zero in some cases with which it can be helpful to estimate the limit of the performance of designed conductors.

In the Figs. 7, 8, and 9, the maximum temperature of CICC was presented during the pulsed operations according to the scenarios. Under the both scenarios, every case showed a safe operation without quenching. However, it is hard to expect from the analysis whether such an extreme operating condition will not arise the problem in any cases.

However, through these analyses, the design of CICC can be verified how suitable it is for PUMA UC, and it was possible to obtain some conservative guidelines for the estimation of the limit of pulsed operational parameters with the specification of individual design of CICC.

And, it seems to be obvious that our preliminary design and analysis for the PUMA-UC achieved a ground of feasibility for the previously planned goal of the magnet system for a test facility.

IV. Summary

To upgrade of PUMA-MC(Main Coil), a new insertion coil was designed for the center field up to ± 12 T with the capability of pulsed operation.

For the design, two types of CICC were specified through the process under the consideration of optimal conductor design. The resultant CICC was analysed by a numerical tool to estimate the minimum quench energy. Each CICC design showed the sufficient temperature margin above 3 K and minimum quench energy of 440 mJ/cc and 680 mJ/cc in the given static condition.

As a heat load during the pulsed operation, the external heat deposition by AC losses was implemented in the numerical code of thermo-hydraulic analysis according to the time varying operation current. Both CICC designs showed robust behaviors under the extreme cases of operation scenario. So we could verify the designs of the conductor of PUMA UC through the thermo-hydraulic analysis for estimation of minimum temperature margin with respect to the pulsed operations.

References

[1] P. Bruzzone, M. Bagnasco, D. Ciazynski, R. Herzog, B. Stepanov, and R. Wesche *et al.*, "Test results of two ITER TF conductor short samples using high current density Nb3Sn strands," *IEEE Trans. Appl. Superconductivity*, vol. 17, no. 2, pp. 1370–1373, 2007.

[2] S. K. Baang and K. Kim *et al.*, "The background magnets of the Smasung superconductor test facility," *IEEE Trans. Appl. Superconductivity*, vol. 11, no. 1, pp. 2082–2085, 2001.

[3] A. M. Fuchs, B. Blau, P. Bruzzone, G. Vecsey, and M. Vogel, "Facility status and results on ITER full-size conductor tests in SULTAN," *IEEE Trans. Appl. Superconductivity*, vol. 11, no. 1, pp. 2022–2025, 2001.

[4] S. Lee, B. Lim, S. Baang, M. Kim, H. Park, J. Kim, I. Han, B. Lee, and K. Kim, "Fabrication of the cables for the background-filed magnet system of SSTF," *IEEE Trans. Appl. Superconductivity*, vol. 12, no. 1, pp. 583–585, 2002.

[5] L. Bottura, "Study of stability and protection of CICC's—An updated designer's view," *Cryogenics*, vol. 38, pp. 491–502, 1998.

[6] H. C. Kim, D. K. Oh, S.-H. Park, K. Kim, and P. Bruzzone, "Development and Sultan test result of ITER conductor samples of Korea," *IEEE Trans. Appl. Superconductivity*, vol. 18, no. 2, pp. 1084–1087, 2008.

[7] Q. Wang, C. S. Yoon, and K. Kim, "Analysis on stability margin of $\mathrm{Nb_3Sn}$ cable-in-conduit-conductor," *IEEE Trans. Appl. Superconductivity*, vol. 10, no. 1, pp. 693–696, 2000.

[8] W. Chung, S. Park, and Q. Wang *et al.*, "Thermo-hydraulic analysis of the KSTAR central solenoid model coil," *IEEE Trans. Appl. Superconductivity*, vol. 15, no. 2, pp. 1411–1414, 2005.

[9] Q. Wang, C. S. Yoon, J. He, W. Chung, and K. Kim, "Operation temperature margin and heat load in PF superconducting coils of KSTAR," *IEEE Trans. Appl. Superconductivity*, vol. 12, no. 1, pp. 648–652, 2002.